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Characteristic time scales of mixing, mass transfer and biomass growth in a Taylor vortex algal photobioreactor

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HIGHLIGHTS

- Mixing, mass transfer, and biomass growth rates were determined from experiments.
- Biomass growth rate in Taylor vortex reactors is not limited by mass transfer.
- Flow patterns in Taylor vortex reactors improve light delivery to microorganisms.

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ABSTRACT

Recently it has been demonstrated that algal biomass yield can be enhanced using fluid flow patterns known as Taylor vortices. It has been suggested that these growth rate improvements can be attributed to improved light delivery as a result of rapid transport of microorganisms between light and dark regions of the reactor. However, Taylor vortices also strongly impact fluid mixing and interphase (gas–liquid) mass transport, and these in turn may also explain improvements in biomass productivity. To identify the growth-limiting factor in a Taylor vortex algal photobioreactor, experiments were performed to determine characteristic time scales for mixing and mass transfer. By comparing these results with the characteristic time scale for biomass growth, it is shown that algal growth rate in Taylor vortex reactors is not limited by fluid mixing or interphase mass transfer, and therefore the observed biomass productivity improvements are likely attributable to improved light utilization efficiency.

1. Introduction

Development of more efficient algal photobioreactors (PBRs) is driven by increasing interest in algaculture for the production of fuels, chemicals, food, animal feed, and medicine (Spolaore et al., 2006). Even for high-volume applications that require pond systems, such as the production of biofuels, PBRs play an important auxiliary role in maintaining pond cultures. Moreover, because of the better control of mixing and containment of growth media and feed gas offered by PBR systems, the prospect exists for using industrial CO_2 waste streams for cultivation of microalgae (Morweiser et al., 2010). Consequently, there is significant incentive to design and operate algal PBRs with high biomass productivity and conversion efficiency.

Many factors affect performance of PBRs, such as the type of PBR, culture media, temperature, pH, microorganism used, CO_2 mass transfer, O_2 accumulation, mixing, light intensity and light/dark cycles (Kumar and Das, 2012). Among these, the major limiting factors for growth of microalgae are usually light availability and interphase mass transfer. Light limitations caused by absorption and scattering can occur even in dilute cell cultures, depending upon the distance of the light path through the reactor and the intensity of the incident radiation (Hu and Richmond, 1996). Near the reactor irradiated surface, algal radiative exposure is usually adequate or in excess, whereas a dark volume with insufficient light for photosynthesis to occur often resides only a few centimeters or less from the irradiated surface, depending on the cell concentration (Kong and Vigil, 2014). For this reason, a key factor in the design of PBRs is the incorporation of mechanisms to periodically transport cells between light and dark regions of the reactor (mixing-induced light/dark cycles) in order to efficiently utilize radiation near the illuminated reactor surface and distribute it evenly to microorganisms (Hu and Richmond, 1996; Ugwu et al., 2005; Sobczuk et al., 2006; Huang et al., 2014).

Mixing induced light/dark (L/D) cycles usually occur at frequencies on the order of 1 Hz or less, which is significantly lower than the minimum frequencies required to produce the flashing light

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effect (>25 Hz). Nevertheless, it has been demonstrated that photosynthesis can be enhanced by low frequency L/D cycles (Miller et al., 1964; Grobbelaar, 1994; Morweiser et al., 2010; Huang et al., 2014; Takache et al., 2015). In flat-plate (Hu and Richmond, 1996; Janssen et al., 2003), bubble column (Merchuk et al., 1998), and airlift bioreactors (Merchuk et al., 1998; Degen et al., 2001), fluid transport between light and dark regions of the reactor occurs primarily via diffusive processes resulting from bubble-induced mixing, and consequently these reactors do not generate the characteristic L/D cycles required to more evenly distribute light to microorganisms (Liao et al., 2014). As a result, some conventional PBR designs incorporate foils or baffles to generate coherent L/D cycles (Degen et al., 2001; Ugwu et al., 2005; Liao et al., 2014).

As an alternative approach for generating L/D cycles for culturing algae, Miller et al. (1964) used a Taylor–Couette device (fluid confined to the annulus between two concentric cylinders, with the inner cylinder rotating) to generate toroidal Taylor vortices that rapidly and reliably shuttle fluid between the poorly lit inner cylinder and the well-illuminated outer cylinder. Although they performed only short time scale experiments, they were able to demonstrate that the rate of photosynthesis (via oxygen measurements) increased with increasing cylinder rotation speed, and they attributed these enhancements to increases in the L/D frequencies experienced by microorganisms.

More recently, Taylor vortex PBRs have been used to culture *Chlorella vulgaris* to very high concentrations in both batch (Kong et al., 2013) and continuous cultures (Kong and Vigil, 2013), and it has been demonstrated that the biomass yields are significantly greater than those obtained in the absence of Taylor vortices (i.e. an annular bubble column with no cylinder rotation). However, it should be noted that gas–liquid mass transport is also significantly enhanced by the presence of Taylor vortices (Ramezani et al., 2015), and as a result the question arises as to whether algal growth rate enhancements in these devices is attributable primarily to the creation of L/D cycles, to improved interphase mass transport of carbon dioxide and oxygen, or to a combination of both effects. Hence, the purpose of this report is to describe the findings of a series of batch culture experiments designed to determine characteristic times for liquid mixing, gas–liquid mass transfer, and algal biomass growth in a Taylor–Couette PBR for a range of reactor inner cylinder rotation speeds, feed gas flow rates, and feed gas compositions. As a result of these experiments, it can be concluded that improved light delivery is apparently the only plausible physical mechanism that can explain the enhanced algal growth rates observed in Taylor vortex PBRs.

2. Methods

2.1. Organism, media, and subculture

All experiments were carried out using *C. vulgaris* (UTEX #265) grown in a modified M8-a medium having the composition described by Kliphuis et al. (2010). Subcultures were maintained in 250-mL shake flasks at room temperature with an incident photon flux of 10–20 μmol m^{-2} s^{-1} provided by compact fluorescent light bulbs, and agitated by a gas mixture of air enriched with 5% (molar) carbon dioxide. The culture medium was sterilized with a 0.22 μm sterile filter after the pH was adjusted to a value of 6.7 ± 0.1 by adding 2 N potassium hydroxide solution. In the Taylor vortex PBR, the solution pH depends upon the carbon dioxide gas–liquid equilibrium, and it was consistently measured during culture conditions to be in the range of 7.0–8.0. In all experiments reported here, the PBR was inoculated at cell dry biomass concentration of 0.067 g/L, as determined from optical density measurements.

2.2. Photobioreactor

A 3D rendering of the Taylor–Couette PBR used in this study can be found in Gao et al. (2015), and a schematic diagram of the batch culture system is shown in Fig. 1. The fixed outer cylindrical reactor wall and surrounded heating jacket were constructed using transparent Plexiglas. The diameters of the rotating inner and fixed outer cylinders were 7.62 and 10.16 cm, respectively, resulting in an annular gap width of 1.27 cm. The length of the reactor (48 cm) provided an annular working volume of approximately 1.7 L. The stainless steel inner cylinder was rotated by a stepper motor (Applied Motion Products, STM24SF) mounted at the top of the reactor. Sterilization of the annular reaction chamber was achieved by filling it with a solution of 70% alcohol followed by rinsing with autoclaved deionized water. The reactor temperature was maintained at 37 °C by circulating water through the reactor jacket using a NESLAB Instruments EX-221 water bath circulator. The reactor was enclosed along its length by four Hydrofarm eco-4441B flat light panels, each of which was comprised of four T5 fluorescent light tubes. The photosynthetic photon flux on the surface of the reactor (external surface of the heating jacket) was measured to be 450 μmol m^{-2} s^{-1} using a LICOR LI-190 2 quantum sensor connected to a LI-250 light meter. The feed gas, consisting of a binary mixture of nitrogen and carbon dioxide (6–12 mol% CO_2) at a total flow rate of 85–510 mL/min (0.05–0.30 vvm) was first passed through a sterile filter and then pumped into the reactor via four 40-μm sureseal miniature mufflers (McMaster-Carr, type H) arranged symmetrically inside the bottom end cap of the reactor. The inlet gas flow rate of each gas component was controlled by digital gas flow controllers and the off-gas flow rate was measured using a gas flow meter. Further details concerning the apparatus and procedure can be found in Kong et al. (2013).

2.3. Experimental measurements

The mole fractions of carbon dioxide and oxygen in the off-gas were continuously measured and recorded throughout each experiment at 10 min intervals by passing the off-gas through a gas analyzer (Quantek Instruments, 902P, Grafton, MA) connected downstream of a desiccant purifier (Drierite, L68GP). The biomass concentration was monitored at 6–12 h intervals by extracting culture samples from the reactor using a syringe and measuring optical density. In addition, dry biomass was determined from 10 mL reactor broth samples that were centrifuged at 3400 rpm for 12 min, freeze-dried for 48 h, and weighed using a balance with 0.1 mg resolution. The relationship between optical density (OD_{680}) and dry biomass (C_b), as previously determined from hundreds of measurements in our earlier work (Kong et al., 2013; Kong and Vigil, 2013), is well represented by the following correlation,

$$C_b\ (\mathrm{g/L}) = 0.33(\mathrm{OD}_{680}), \qquad R^2 = 0.997. \tag{1}$$

Because of the reliability of the above relation, dry biomass was not weighed at every sampling interval; in some instances biomass concentration was computed from optical density measurements, thereby reducing the culture volume loss during the course of an experiment.

Elemental composition (C, H, N and S) of dry biomass samples was determined using an elemental analyzer (Perkin Elmer 2100 Series II CHN/S Analyzer). Dry biomass samples were first freeze-dried for 48 h and subsequently heated in an oven at 65 °C for an additional 48 h to completely remove water before they were